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WIND ESTIMATES FROM CLOUD MOTIONS: PHASE 1 OF AN IN SITU AIRCRAFT VERIFICATION EXPERIMENT

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WIND ESTIMATES FROM CLOUD MOTIONS: PHASE 1 OF AN IN SITU AIRCRAFT VERIFICATION EXPERIMENT

by

A. F. Hasler,[1] W. Shenk and W. Skillman

Abstract

An initial experiment has been conducted to verify geostationary satellite derived cloud motion wind estimates with in situ aircraft wind velocity measurements. The experiment was conducted during December 1972 over the Caribbean Sea with the following aircraft: the National Center for Atmospheric Research (NCAR) Buffalo and Sabreliner, and the NASA and U.S. Air Force RB-57F's. The Buffalo and Sabreliner were used for in situ wind velocity measurements and cloud height determinations, and the RB-57F's for precision aerial photogrammetry. Case histories of one-half hour to two hours were obtained for 3-10km diameter cumulus cloud systems on 6 days. Also, one cirrus cloud case was obtained. In most cases the clouds were discrete enough that both the cloud motion and the ambient wind could be measured with the same aircraft Inertial Navigation System (INS). Since the INS drift error is the same for both the cloud motion and wind measurements, the drift error subtracts out of the relative motion determinations. The magnitude of the vector difference between the cloud motion and the ambient wind at the cloud base averaged 1.2 m sec^{-1}. The wind vector at higher levels in the cloud layer differed by about 3 m sec^{-1} to 5 m sec^{-1} from the cloud motion vector.

[1] Affiliated with the National Center for Atmospheric Research at the time this experiment was carried out.

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1. Introduction

For long range prediction of the state of the atmosphere by numerical models, it is necessary to define the present state of the atmosphere on a global basis. The ocean areas of the world are particularly devoid of conventional radiosonde data. Furthermore, because the Coriolis relationship breaks down at low latitudes, wind velocity becomes the definitive quantity for the description of the atmosphere in the tropics. It is particularly fortunate that cloud motions derived from geostationary satellites can provide a method of estimating the winds at some of the required levels in these regions where they are most needed. Cloud motion wind estimates are already in operational use by NOAA in their global numerical prediction model. The second generation geostationary satellite images provide a superb tool for investigating mesoscale phenomena such as severe thunderstorms in which wind is also the definitive parameter because of the short time scale involved. For these reasons it is extremely important to verify the accuracy and reliability of the cloud motion-wind estimates.

Previous evaluations of cloud tracers as wind estimators have been made using comparisons with rawinsonde measurements. Some of these studies are described by Fujita et al. (1969), Hasler (1972), Hubert and Whitney (1971), and Serebreny et al. (1970). This evidence has been obtained primarily from comparisons of cloud tracers whose height is only roughly estimated, with rawinsonde winds up to 250km distant and up to three hours removed in time. In addition to the disadvantageous time and space separation, the independent errors in the cloud motion measurements and rawinsonde wind measurements, as well as the island orographic effects on the rawinsonde, must be considered. Finally, because the rawinsonde balloon is a very small object passing quickly through a layer, it may not be representative of the large scale motions. For these reasons previous evaluations of cloud motion wind estimates are not completely definitive. The comparisons between cloud motions and rawinsonde winds most likely place only an upper limit on the difference between the cloud motion and the true wind.

An improved evaluation of wind estimates from cloud motions results from performing sufficiently accurate in situ measurements of cloud motion and height as well as ambient wind velocity.

2. Techniques

Figure 1 shows the nominal aircraft flight patterns used in this experiment. Low level aircraft were used to define the vertical extent and development of the cloud, while simultaneously measuring the ambient wind field. Aerial photographs from a high level aircraft were used to measure the cloud motion. Finally the results were compared with the cloud motions derived from ATS-3 satellite pictures. In the course of conducting the experiment, it was discovered that the clouds were so well defined that the low level aircraft could also be used to measure the cloud position with respect to time thus permitting a third determination of cloud motion.

The Sabreliner and Buffalo from NCAR were used to measure cloud heights and the ambient wind velocity. The vertical extent and development of the cloud are quantities which are determined poorly, if at all, in previous studies. In this experiment the cloud height was determined by having the pilot adjust the aircraft altitude until the plane reached the cloud base, or top, and then reading the altitude from the pressure altimeter. For measurement of the ambient wind velocity, each aircraft was equipped with an INS platform and the standard instruments for determining true air speed such that it was able to measure the wind with an accuracy of approximately 1.4 m sec^{-1} (Kelley and Zruber, 1973). As illustrated in Fig. 1, the wind measurements were taken from one minute averages on straight and level flight legs at 150 m, cloud base, mid-cloud, and cloud top. Discrete cloud tracers with long lifetimes were found near enough to the base of operations so that they could be tracked by the aircraft for long periods. The location of the cloud center was done by measuring cloud entrance, center, and exit on each pass. The cloud centers were generally measured by the low level aircraft within one km at five minute intervals. The method of computing cloud motion from these data was as follows: (1) The cloud motion direction was obtained from a least squares fit of successive cloud positions; and, (2) the cloud speed was computed from the sum of the components parallel to the least squares direction, divided by the time difference between the first and last cloud position. For a cloud track of one hour using the first and last cloud location only, the cloud motion error due to the error in center determination of one km is 0.35 m sec^{-1}. In order to estimate the error when all the cloud tracking data was used, a random error with a standard deviation of one km/ $\sqrt{2}$ was added to the x and y coordinates of each cloud location. Then the absolute value of the vector difference between the cloud velocity with and without the random error was determined 25 times for each of the 7 cloud tracks. For all 7 tracks, averaging 0.9 hours in length, the average vector difference is 0.32 m sec^{-1}, so apparently there is a slight improvement in accuracy using all the tracking data even over the shorter time interval. Combining the 0.32 m sec^{-1} with the nominal INS drift error of 0.5 m sec^{-1} gives a total error of 0.6 m sec^{-1} in the cloud motion measurement by the low level aircraft.

High level aerial stereo photographs were taken by the NASA and U.S. Air Force RB-57F's. The NASA RB-57F had an INS which enabled the second measurement of the motion of the cloud being tracked by the low flying aircraft plus the measurement of the motion of other nearby clouds. The cloud center was estimated on the RB-57F photographic series as a function of time. These locations, plus aircraft position, heading, and altitude, permitted the determination of cloud center position on the earth. Often the position was not the center of the most active convective tower, but the center of an ensemble of convective towers. This situation occurred primarily when the individual towers were small. A group of six independent meteorologists estimated the centers of the clouds on a few selected photographs to determine the possible error in establishing the center locations. The r.m.s. error was 0.5km. For a cloud tracked for 1 hour, this r.m.s. location error would lead to an incorrect cloud motion estimate of 0.15 m sec^{-1}. Adding the motion error due to center determination statistically to the nominal INS error of 0.5 m sec^{-1} does not change the error significantly. The clouds which were tracked in the RB-57F photographs have been positively identified as the ones which were tracked by the low level aircraft. The series of RB-57F pictures in Fig. 2 shows the conservative nature of the cloud patterns which were tracked. The "V" shaped pattern which is seen in Fig. 2 maintained its basic shape for well over one hour, although the individual cells which make up the pattern lasted for only a few minutes.

Measurements from ATS-3 satellite photographs were used as the third measurement of the cloud motions. It was difficult to identify in the satellite pictures the exact clouds which were tracked by the aircraft. Figure 3 shows the one case in which the cloud tracer was large enough to be identified with reasonable certainty in the satellite picture. In Fig. 3 a small cumulonimbus is seen from three different perspectives; from the low level aircraft, the high level aircraft, and the satellite. When no positive identification was possible, a number of cloud tracers in the vicinity were used. The cloud motion measurements were made from the satellite pictures using a precision "blink" alignment and measuring system. This system was constructed according to specifications of A. F. Hasler at NCAR by the University of Wisconsin Space Science and Engineering Center. The "blink" system, illustrated in Fig. 4, allows two 9" x 9" images, oriented at right angles to each other to be viewed alternately through a half silvered mirror. The blinking is produced by fluorescent back-illumination which can be strobed at continuously variable rates. The lower image can be moved by a precision stage with respect to the x, y, and z (rotation) axes. A movable telescope allows paralax-free viewing so that accurate alignment of two landmarks can be accomplished. Precision micrometers measure the motion of the stage in the x and y axes. Once the two images are aligned, the micrometer dials are set to zero. Then the images are strobed and the lower image is moved until the apparent motion of the tracer cloud is reduced to zero and the incremental displacement of the stage is read from the micrometer dials. This technique uses the human eye as an optical correlator. Because there were good landmarks near the cloud tracking locations, the ATS-3 cloud motion measurements for a 3 hr. interval were accurate to about 0.5 m sec^{-1}, as indicated by Hasler (1972).

3. Results

The cumulus clouds ranged in size from 3-14 km and the cloud bases were near the 960 mb level for the 7 cumulus clouds, and near 350 mb for the cirrus cloud. Most of the cumulus clouds had tops at about 700 mb while the top of the small cumulonimbus on December 14 reached a maximum near 200 mb. The cirrus cloud had a thickness of 50 mb.

Table 1 shows the results for all seven days. In three cases the Sabreliner cloud base wind measurements were made about 130 km away upon descent to Ramey Air Force Base in Puerto Rico. Table 1 shows the results of the three independent measurements of cloud motion. For all seven days, the magnitude of the vector difference between the aircraft measured cloud motions and cloud base wind averages 1.2 m sec^{-1}, as shown on Table 2. This excellent agreement is thought to be possible only because both quantities were measured by the same system. Because the ambient wind measurement and the cloud motion measurement are made using the same aircraft INS platform, the INS drift error is identical in this case and can be subtracted out. The cloud speed averages 0.3 m sec^{-1} greater than the cloud base wind speed and the cloud moves 3° to the right of the wind on the average. However, since these errors are less than the instrumental error, the systematic bias of the wind estimate was considered negligible. The vector difference between the ATS-3 satellite measured cloud motions and the cloud base wind averages about 1.4 m sec^{-1}. This is excellent when it is considered that the clouds which were tracked by the aircraft in most cases have not been positively identified in the satellite pictures. Finally, the measurements made from the INS navigated RB-57F aerial photographs give a vector difference of about 1.7 m sec^{-1} from the cloud base wind. It is also apparent from Table 2 that the wind at higher levels in the cloud did not compare as well with the cloud motion. The mid-cloud and cloud top wind vectors differed from the cloud motion by 3.4 m sec^{-1} and 5.5 m sec^{-1}, respectively.

From the aircraft photographic time series, such as the one shown in Fig. 2, it is apparent that a high frequency of observation is necessary for accurate tracing of cells with short life times. The pattern seen in Fig. 2 is about 15km across and is probably representative of the smallest feature which can be tracked at the standard 30 min geostationary satellite picture interval. The 5-10 min frequency of the aerial photographic time series allows the tracing of smaller features and observation of their development. Furthermore, other larger, more isolated cells extending to higher altitudes were observed which had complete life cycles on the order of 30 min. The higher picture frequency would also be required in order to observe the evolution of these large cells. For tracing the evolution of cells from geosynchronous satellites, higher frequency measurements become especially important as sensor spatial resolution increases, thus permitting smaller clouds with shorter lifetimes and rapid changes to be tracked.

4. Conclusions

The small data set contained in this experiment has provided evidence which indicates that trade wind regime cumulus clouds and isolated cirrus clouds do move within about 1 m sec^{-1} of the wind at the cloud base. Furthermore, the systematic difference between the cloud motions and the wind velocity is negligible.

The following tentative conclusions based on this data can be made regarding future satellite data extraction techniques and future satellite design specifications: (1) knowledge of cumulus cloud top height is not as critical as earlier believed due to the close relationship between the cloud motion and the wind at the cloud base; (2) a frequent observation interval (5-10 minutes) is a substantial asset for assuring continuity; and (3) a 1 m sec^{-1} difference between the cloud motion and the wind places definite constraints on the spacecraft and sensor by requiring these accuracies from space measurements.

The primary direction of further work, some of which is in progress, is to increase the sample size. Data must be obtained under varying weather regimes, different geographical regions, and for different cloud types, particularly cirrus. Future experiments must seek to positively relate the clouds tracked by the aircraft to the geostationary satellite pictures. In this data set, the wind measurement is generally made only once, over a very short time and space interval; future experiments must attempt to estimate the representiveness of the cloud motion vector over larger intervals. Further work will also include the examination of cloud size versus wind velocity. This can be done from the aerial photographs, since the whole cloud field is observed. It may also be possible to examine the relationship of wind vs the orientation of cloud streets. Further analysis in progress includes the measurement of cloud top heights using stereo techniques with the aerial photographs. Finally, filterwheel infrared spectrometer data was obtained by the high level aircraft. It may be possible to use this data to investigate techniques for measuring cloud height using present and future geostationary satellite data systems.

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Table 1

Wind Estimates from Cloud Motions
December 1972 Results of an In Situ Aircraft Verification Experiment

Date	Cloud Motion						Cloud Base Wind		Mid-Cloud Wind		Cloud Top Wind	
	ATS-3 Satellite		RB-57F		Sabreliner		Sabreliner		Sabreliner		Sabreliner	
(Dec.)	Speed (m sec^{-1})	Direction (deg)	Speed (m sec^{-1})	Direction (deg)	Speed (m sec^{-1})	Direction (deg)	Speed (m sec^{-1})	Direction (deg)	Speed (m sec^{-1})	Direction (deg)	Speed (m sec^{-1})	Direction (deg)
4	4.5	105	—	—	4.4	95	4.1	110	3.6	125	3.6	140
5*	21.9	251	—	—	20.5	265	20.6	262*	20.6	261*	20.6	261
9	12.6	73	14.9	78	12.8	81	12.9	73	10.3	100	6.7	80
11	8.9	73	8.2 9.3	70 81	—	—	10.3	70***	—	—	—	—
12**	14.4	80	12.9 11.8	73 70	13.6 13.0	77 77**	13.9	75***	—	—	—	—
13	17.8	94	16.0	92	15.9	101	16.5	95	18.0	87	19.0	100
14	15.4	99	15.4	100	15.2	101	16.0	98***	14.9	110	5.7	89

*The cloud tracked on Dec. 5 was cirrus with a thickness of 50 mb.
**The aircraft tracked two clouds on Dec. 12.
***Measurement made on descent to Ramey AFB, P.R. approximately 130 km away.

Table 2

Magnitude of the Vector Difference Between Cloud Motion and the Ambient Wind Velocity

Date (December)	Difference Between Sabreliner Cloud Motion and the Following: Cloud Base Wind $\lvert\vec{V}_{SL} - \vec{V}_{CBW}\rvert$ (m sec^{-1})	Mid-Cloud Wind $\lvert\vec{V}_{SL} - \vec{V}_{MCW}\rvert$ (m sec^{-1})	Cloud Top Wind $\lvert\vec{V}_{SL} - \vec{V}_{CTW}\rvert$ (m sec^{-1})
4	1.1	2.2	3.1
5	1.1		
9	1.8	4.5	6.1
12	0.6, 1.0		
13	1.8	4.6	3.1
14	1.1	2.4	9.7
Mean	1.2	3.4	5.5
Standard Deviation	0.4	1.3	3.1

Date (December)	Cloud Motion vs Cloud Base Wind: RB-57F $\lvert\vec{V}_{B-57} - \vec{V}_{CBW}\rvert$ (m sec^{-1})	ATS-3 $\lvert\vec{V}_{ATS-3} - \vec{V}_{CBW}\rvert$ (m sec^{-1})
4		0.5
5		4.3
9	2.3	0.3
11	2.1, 2.1	1.5
12	1.1, 2.4	1.2
13	1.0	1.3
14	0.8	0.7
Mean	1.7	1.4
Standard Deviation	0.7	1.4

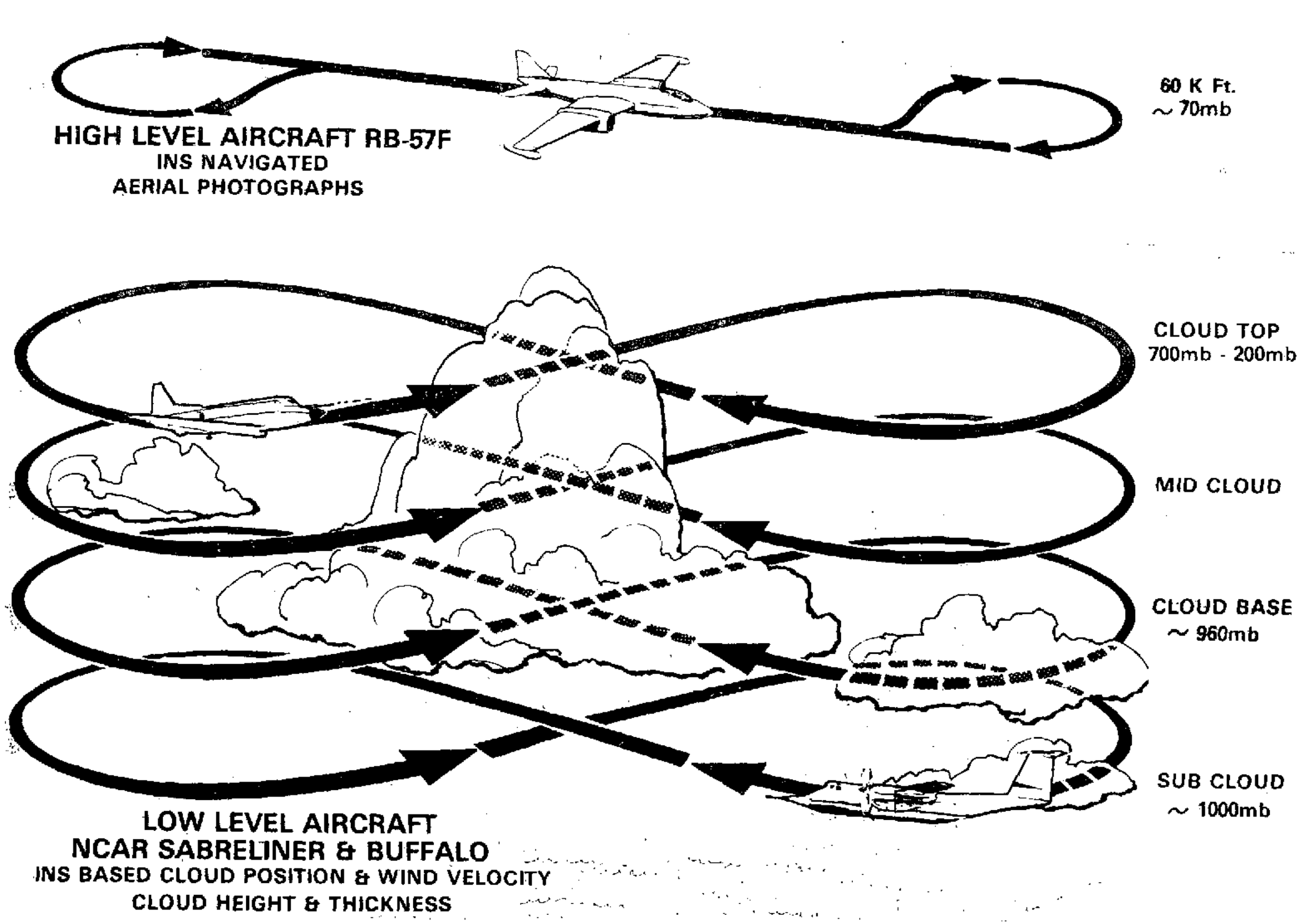

Figure 1. Nominal Aircraft Flight Patterns

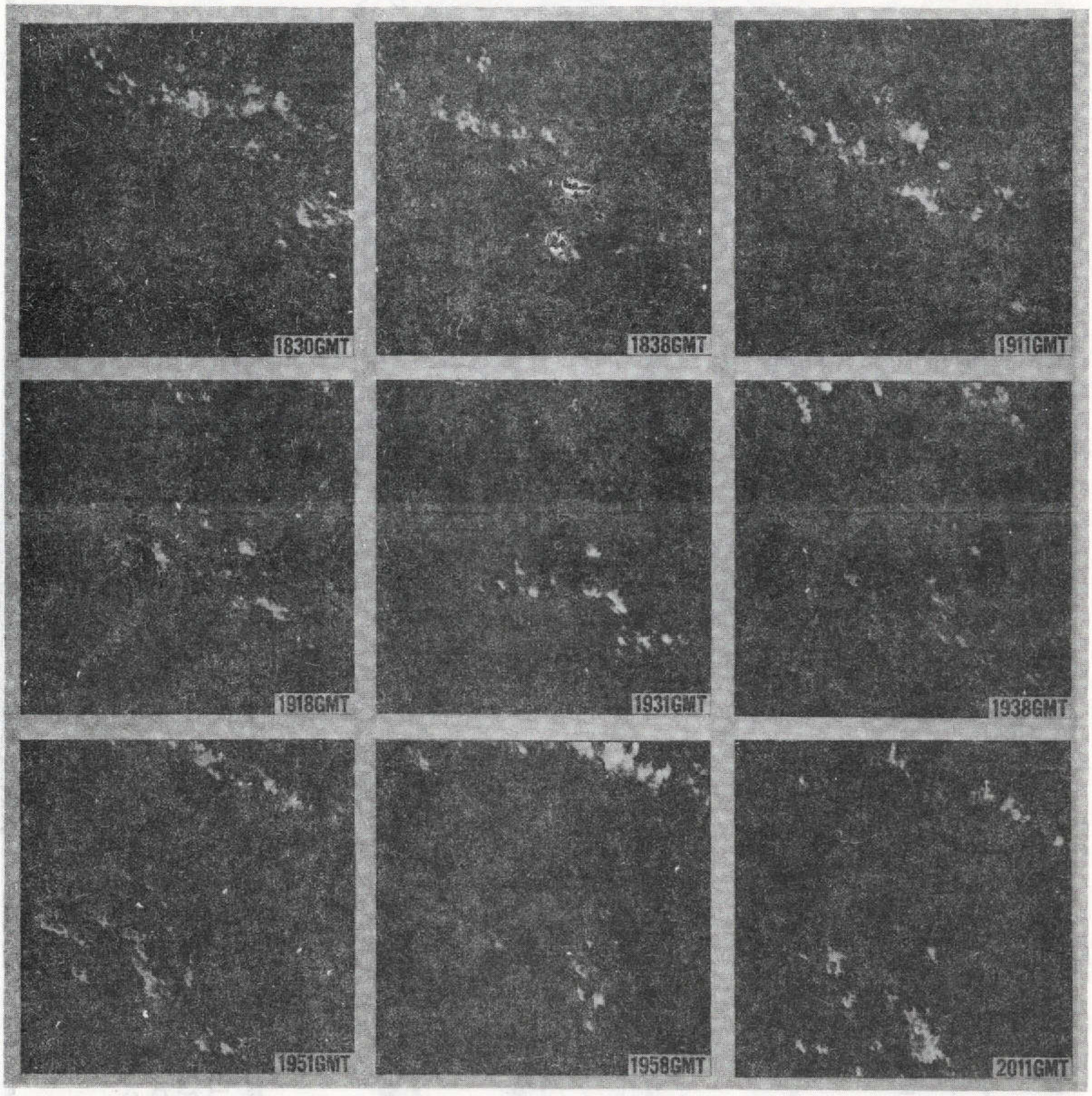

Figure 2. RB-57F Aerial Photographic Sequence of a "V" Shaped Cumulus Cloud Pattern Near Puerto Rico on December 11, 1972

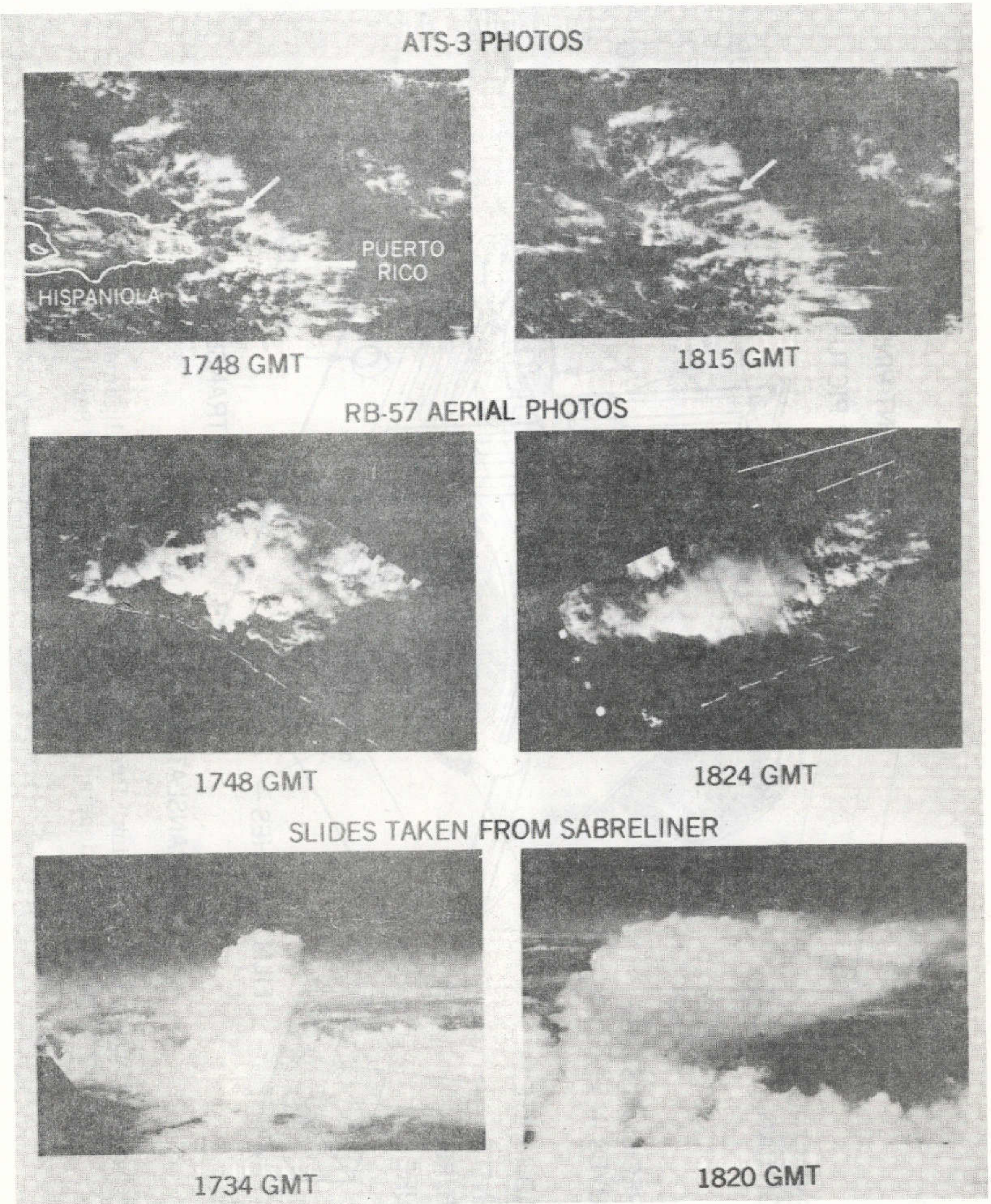

Figure 3. A Small Cumulonimbus on December 14, 1972 as Seen from Three Perspectives; from the ATS-3 Satellite, the RB-57F, and from the NCAR Sabreliner

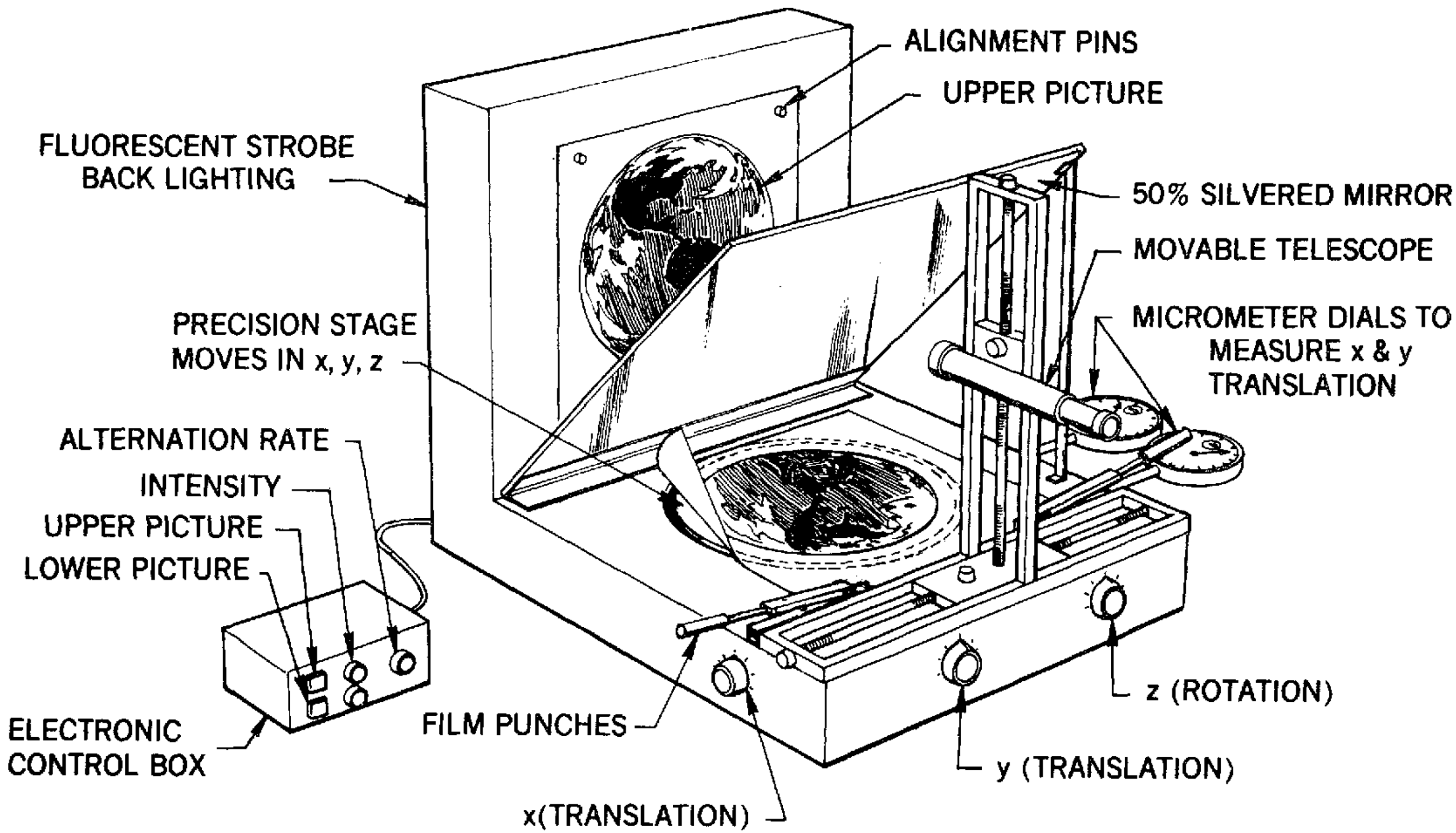

Figure 4. A Schematic Drawing of the "Blink" Precision Measurement and Alignment System for Measuring Winds from Cloud Motions as Seen from Geosynchronous Satellites